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LETTERS

Atlantic hurricanes and climate over the past 1,500 years

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Atlantic tropical cyclone activity, as measured by annual storm counts, reached anomalous levels over the past decade[1]. The short nature of the historical record and potential issues with its reliability in earlier decades, however, has prompted an ongoing debate regarding the reality and significance of the recent rise[2–5]. Here we place recent activity in a longer-term context by comparing two independent estimates of tropical cyclone activity over the past 1,500 years. The first estimate is based on a composite of regional sedimentary evidence of landfalling hurricanes, while the second estimate uses a previously published statistical model of Atlantic tropical cyclone activity driven by proxy reconstructions of past climate changes. Both approaches yield consistent evidence of a peak in Atlantic tropical cyclone activity during medieval times (around AD 1000) followed by a subsequent lull in activity. The statistical model indicates that the medieval peak, which rivals or even exceeds (within uncertainties) recent levels of activity, results from the reinforcing effects of La-Niña-like climate conditions and relative tropical Atlantic warmth.

A number of past studies have attempted to place modern Atlantic tropical cyclone activity in a longer-term context using regional proxy evidence of past landfalling Atlantic hurricanes (tropical cyclones with maximum sustained surface winds exceeding 74 miles per hour)[6–8]. Some studies[4] have sought to infer past changes in activity from plausible local conditioning factors such as wind strength and sea surface temperature (SST), though the interpretations of these studies have been contested[5]. Qualitative comparisons between palaeohurricane reconstructions appear to show some temporal coherence[8,9]. However, no past studies have attempted to synthesize multiple records from distinct regions into a basin-integrated reconstruction of Atlantic hurricane activity. Moreover, no past studies have sought to quantitatively relate estimated variations in hurricane or tropical cyclone activity to reconstructions of the key large-scale climate factors known to have a significant influence on modern Atlantic tropical cyclone activity. Here we produce an empirical record of past landfalling Atlantic hurricane activity by combining information from multiple sedimentary records of hurricane-induced overwash. Further, we compare these resulting estimates to independent statistical model predictions of past tropical cyclone activity driven by proxy-based large-scale climate reconstructions.

Sediment-based overwash reconstructions of hurricane landfall are limited in number, but span a wide geographic area across the North Atlantic basin affected by hurricanes. Our compilation includes (see Fig. 1) a site from the Caribbean (Vieques, Puerto Rico[6,9,10]), one from the US Gulf Coast[7], one from the southeastern US coast[11], three from the mid-Atlantic coast (one from New York[8] and two from New Jersey[12,13]) and two from southeastern New England (one from Rhode Island[14] and another from Massachusetts[15]), yielding five distinct regional series. We obtained a probabilistic estimate of past basin-wide landfalling hurricane activity using an appropriately weighted combination of the information from these five regional series, and incorporating radiocarbon age model uncertainties.

An independent estimate of past tropical cyclone activity was obtained using a statistical model for Atlantic tropical cyclone counts. This previously developed and validated[3,16] statistical model conditions annual Atlantic tropical cyclone counts on three key large-scale climate state variables tied to historical variations in Atlantic tropical cyclone counts: (1) the SST over the main development region (MDR) for tropical Atlantic tropical cyclones, which reflects the favourability of the local thermodynamic environment; (2) the El Niño/Southern Oscillation (ENSO), which influences the amount of (unfavourable) vertical wind shear; and (3) the North Atlantic Oscillation (NAO), which affects the tracking of storms,

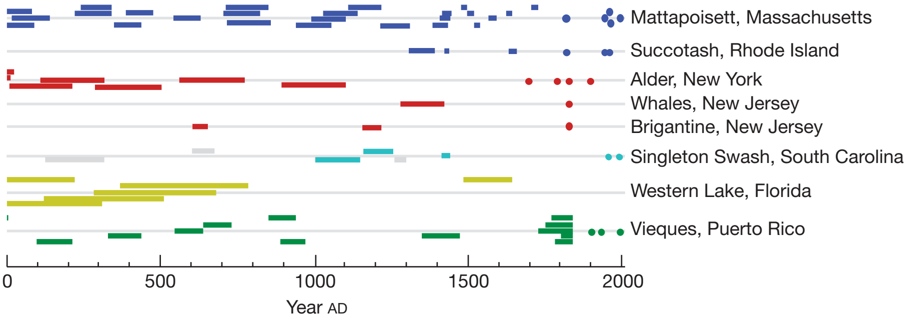

Figure 1 | Overwash sediment records of landfalling hurricanes. Event histories are shown for New England (blue), Mid-Atlantic (red), the southeastern US coast (turquoise; grey denotes oyster-bed events not used for reasons discussed by ref. 28 and in the Supplementary Information), the Gulf Coast (yellow) and the Caribbean (green). The horizontal width of shaded rectangles indicates the ±1σ age model uncertainties. Circles indicate historical hurricane events.

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determining how favourable an environment they encounter. The statistical model was driven by proxy-based reconstructions[17,18] of these three state variables (Fig. 2), yielding a predicted history of Atlantic tropical cyclone counts for past centuries.

We compared the sediment-based record against the above statistical estimate of basin-wide tropical cyclone activity (Fig. 3), guided by a working assumption that an appropriately weighted composite of regional landfalling hurricane activity varies, at multidecadal and longer timescales, in rough proportion to basin-wide tropical cyclone activity. Although the validity of this assumption can (as discussed further below) be questioned, it is worth noting that the sediment-based record tracks the observed long-term changes in tropical cyclone count over the historical period remarkably well (inset, Fig. 3). On the basis of previously published results, the required storm strength required for overwash and deposition varies among sites[19], although qualitatively similar results were obtained assuming uniform sensitivity (category 3 or greater storms) among sites (Supplementary Information). We down-weighted the Vieques data after AD 1700 to account for an estimated[9,10] artificial inflation of overwash deposit occurrences at the site due to increased sedimentation rates in recent centuries.

Our two entirely independent estimates of past tropical cyclone activity were found to be statistically consistent (that is, they overlap within their estimated 95% confident intervals), with certain exceptions, which are discussed below. Jointly, the two independent records suggest periods of high activity (that is, comparable to current levels) during a medieval era of roughly AD 900–1100. Both estimates also suggest a general decrease in the level of activity after about AD 1200[6,9].

Of particular interest is the medieval peak in activity, which matches or even exceeds current levels of activity within uncertainties for the statistical model. The peak arises in the statistical model from a combination of (see Fig. 2) La-Niña-like conditions during the medieval era which have been discussed elsewhere[20–22] and relatively warm SSTs in the tropical North Atlantic at that time[23,24], with both of these factors having a substantial role in the statistical model predictions (Supplementary Information). In contrast, this interval is followed by a combination of relatively cold Atlantic SSTs and more El-Niño-like conditions in the tropical Pacific, leading to a relative lull in modelled tropical cyclone activity in subsequent centuries before the modern increase. This finding is in contrast to some other recent work[4], because we do not find hurricane activity during the 1970s to be anomalously low in comparison with that over the past few centuries.

There are also some noteworthy discrepancies between the two independent estimates of past Atlantic tropical cyclone activity provided in this study. There is some independent historical

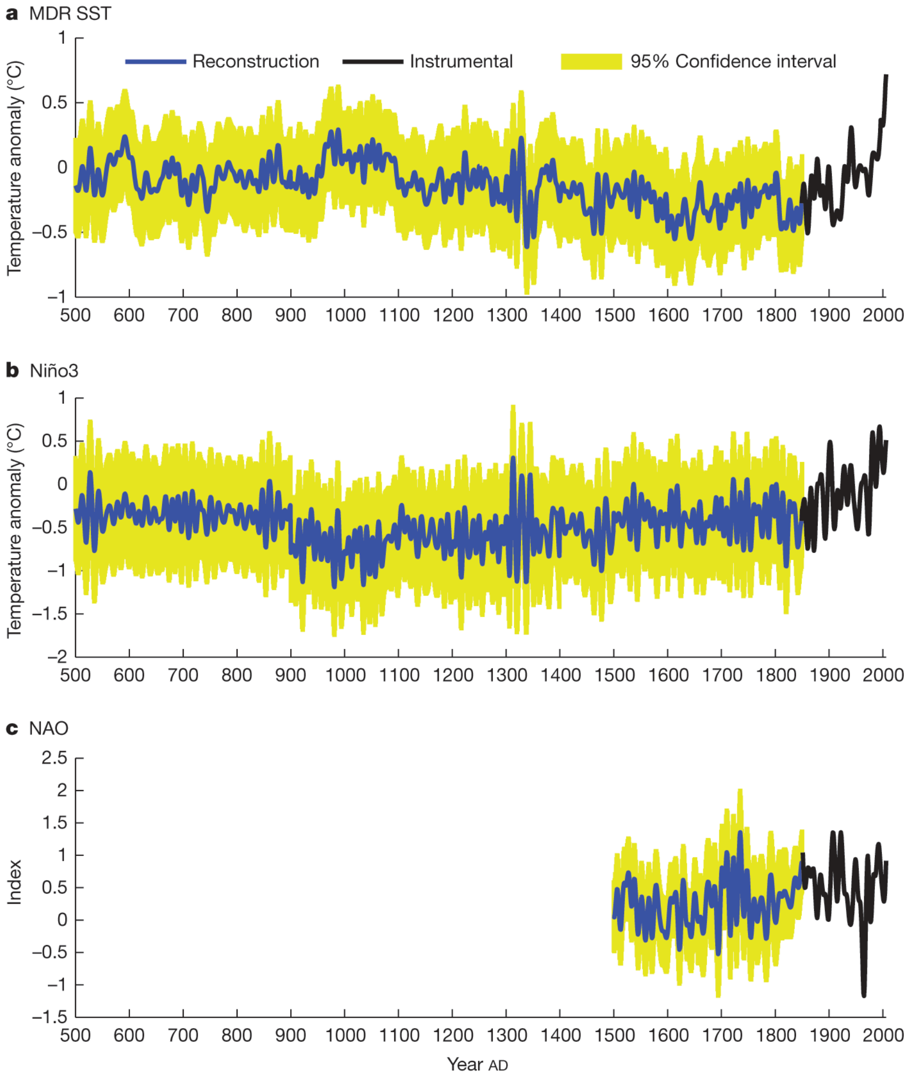

Figure 2 | Proxy reconstructions used in statistical model estimates of Atlantic tropical cyclone counts. **a**, The MDR SST[17]; **b**, the Niño3 SST[17]; and **c**, the boreal winter NAO[18]. Positive indices are associated with enhanced (**a**) and diminished (**b**, **c**) tropical cyclone activity, respectively[16]. The corresponding instrumental series[17,18] are shown for comparison. All series are decadally smoothed[30], and 95% uncertainty intervals are indicated by yellow shading.

documentary evidence for increased tropical cyclone activity in the Caribbean during the 1760s–1780s[25], and a modest peak at this time is evident in the statistical model estimate. The sediment-based estimate, however, displays a peak that is later (early nineteenth century), and of considerably greater magnitude. The medieval peak in the sediment-based record falls slightly later than in the statistical model estimate, and is of greater duration. The peak in activity indicated by the sediment record in the mid-fifteenth century is not seen in the statistical model results.

There are a number of plausible explanations for the differences between the two records. Landfalling hurricanes do not vary in fixed proportion to the total number of storms generated on decadal timescales[1]. A form of the well known 'ergodic hypothesis' holds that on increasingly longer averaging timescales (for example, the centennial timescale variations of interest in this study), variations in totals among the considerably sparser group of landfalling hurricanes will more closely mirror those in the larger group of basin-wide tropical cyclones. However, certain predictors, such as the NAO, influence not only the basin-wide activity but also the prevailing regions of landfall, and given an incomplete coastal observing network, a change in the latter could potentially masquerade as a change in the former. The sites used to produce a basin-wide sediment composite record may simply not be representative enough of the true, full basin-wide activity. This caveat applies in particular to the Caribbean, Gulf Coast and southeast US coast, because we are relying on just one record in each case to estimate past tropical cyclone activity in these regions. A jackknife estimate of uncertainty based on the removal of any one of the five contributing regions (Fig. 3) nonetheless suggests that the main features of our basin-wide composite are reasonably robust (the individual jackknife surrogates are shown in Supplementary Information).

The sediment record could be contaminated by influences unrelated to hurricane strikes such as alterations to barrier morphology[26,27]. Also, potential biases in the proxy-based palaeoclimate reconstructions[17,18] used to drive the statistical model would of course lead to biases in the statistical model predictions themselves. Finally, there is the possibility that other potential tropical cyclone influences (for example, the West African monsoon[6]) not accounted for in the statistical model (that is, that are not correlated with the three predictors used), may have had a more important role in the past than is evident during the modern interval.

Such uncertainties and caveats notwithstanding, the striking consistency of certain key features such as the medieval peak in Atlantic tropical cyclone activity and subsequent lull using two entirely independent approaches to estimating past activity suggest that these features are real, and provides some degree of additional validation of our current understanding of the primary factors governing long-term changes in Atlantic tropical cyclone activity. Paths forward that may further improve our understanding include, among other things, development of a more extensive and diverse set of multi-proxy estimates of past landfalling hurricane activity, and improved reconstructions of the past histories of key large-scale

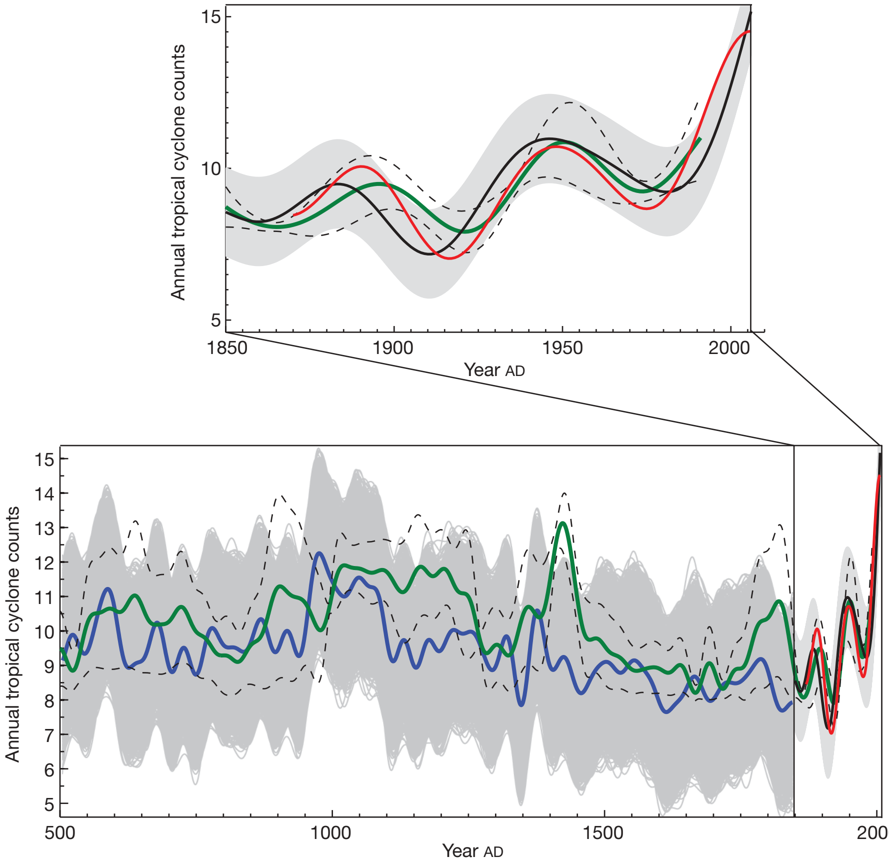

Figure 3 | Long-term Atlantic tropical cyclone counts. Modern Atlantic tropical cyclone counts (red) compared both with statistical model estimates of tropical cyclone activity based on modern instrumental (AD 1851–2006; black) and proxy-reconstructed (AD 500–1850; blue) climate indices and an estimate of basin-wide landfalling Atlantic hurricane activity (AD 500–1991) derived from regional composites of overwash sediments (green). All series were smoothed[30] at multidecadal (>40-year) timescales. The sediment composite record was standardized to have the same mean and multidecadal variance as the statistical model estimates. Uncertainties for the statistical model estimates (grey shading, indicating 95% confidence intervals) take into account the uncertainty in the statistical model itself (grey shading), and—in the case of the proxy-reconstructed indices (grey shading), the additional uncertainty due to the uncertainties in the proxy-reconstructed climate indices. Uncertainties for the sediment composite record (thin dashed black curves indicating upper and lower limits of the 95% confidence interval) are derived from jackknifing of the full composite with respect to each of the five contributing regional estimates, as discussed in the text.

climate phenomena influencing Atlantic tropical cyclones such as ENSO.

METHODS SUMMARY

Sediment hurricane landfall records. Regional sediment series were weighted with respect to inverse modern return periods for landfalling tropical cyclones[19] and summed to yield basin-wide composites of tropical cyclone activity. We used a Monte Carlo approach to generate an ensemble of such composites consistent with the event chronologies and age model uncertainties. A basin-wide landfalling hurricane activity series was defined by the maximum rate of activity for each year over this ensemble, that is, the maximum rate of activity for each year that is consistent with the event chronologies within uncertainties. We examined sensitivity both to the contributions of individual regions (issues of reliability have been raised with some events in the Gulf Coast[27] and southeastern US coast[28] records), and to the assumed threshold of the sites to overwash from varying strengths of hurricanes (Supplementary Information).

Statistical model. We used a statistical model of tropical cyclone counts as conditioned on[3,16]: the MDR SST, the ENSO (measured by the boreal winter Niño3 SST index), and the boreal winter NAO index. The tropical cyclone count series was first corrected for a modest estimated undercount[3] before the mid-twentieth-century undercount, although similar results were obtained (Supplementary Information) using the largest[2,29] published estimates of undercount bias. The statistical model, which is trained on the modern historical record, has been shown in independent statistical validation experiments[3,16] to resolve roughly 50% of the interannual and longer-term variations in Atlantic tropical cyclone counts. The model, in this study, was driven by decadally smoothed proxy reconstructions of the three required climate indices to yield predictions of tropical cyclone activity over past centuries. The MDR SST and Niño3 reconstructions were derived from proxy-based surface temperature patterns spanning the past 1,500 years[17]. Though an NAO reconstruction was available only for the past 500 years[18], the NAO influence was found to be very minor (Supplementary Information).

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions M.E.M. performed the statistical reconstructions of tropical cyclone and hurricane activity. J.D.W. and J.P.D. provided the sediment overwash records of hurricane landfall and their uncertainties. J.D.W. provided the landfall return period estimates. Z.Z. provided the climate reconstructions used and their uncertainties. M.E.M. primarily wrote the paper. All authors discussed the results and provided input on the manuscript.

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METHODS

Formation of regional sediment series and composites. Regional landfalling hurricane chronologies were formed by combining sediment overwash records that fall within the same distinct five regions back to AD 500. The regions and associated records are:

(1) New England (two records): Mattapoisett Marsh, Massachusetts, 250 BC to present, latitude 41° 39′ 8″ N, longitude 70° 47′ 13″ W (ref. 15); and Succotash Marsh, Rhode Island, AD 1300 to present, 41° 22′ 45″ N, 71° 31′ 17″ W (ref. 14)
(2) the Mid-Atlantic (three records): Alder Island, New York, 238 BC to present, 40° 35′ 54″ N, 73° 34′ 45″ W (ref. 8); Brigantine, New Jersey, AD 600 to present, 39° 25′ 14″ N, 74° 21′ 11″ W (ref. 13); and Whale Beach, New Jersey, AD 1300 to present, 39° 11′ N, 74° 40′ 17″ W (ref. 12)
(3) the southeast US Atlantic Coast: Singleton Swash, South Carolina, AD 223 to present, 33° 46′ N; 78° 47′ W (ref. 11)
(4) the Gulf Coast: Western Lake, Florida, 1726 BC to present, 30° 19′ 38″ N; 86° 08′ 55″ W (ref. 11)
(5) the Caribbean: Laguna Playa Grande Lake, Vieques, Puerto Rico, 3461 BC to present, 18° 5′ 31″ N; 65° 31′ 3″ W (refs 6, 9 and 10)

As discussed in the main article, potential biases have been noted for some of the records used, including the Western Lake record[27] and the Singleton Swash record[28]. For the Singleton Swash record, we made an explicit attempt to deal with certain known problems as discussed in the 'Processing of individual sediment records' section below.

Processing of individual sediment records. The three oyster-bed termination events (AD 223, AD 652, and AD 1283) from the Singleton Swash, South Carolina, record were not included in our analysis because of the uncertainty regarding the attribution for oyster reef terminations to hurricanes[11,28], as well as potentially significant and undefined age uncertainties related to reservoir effects for the dated oyster shell material. In the absence of such a correction, the chronologies of these events do not meet the age control required for our analyses.

We adjusted the Vieques, Puerto Rico, record, on the basis of the likelihood of an artificial trend in sensitivity of hurricane landfall at the site owing to a substantial increase in sedimentation rates since AD 1700 (refs 9, 10). Following ref. 9, we assumed that changes in sedimentation rates result in an undercounting of approximately 11% after 1700 AD compared to 32% before AD 1700, and so we down-weighted the post-AD 1700 Vieques record by a factor of 11%/32% (that is, approximately one-third). Alternatively, we performed an analysis in which the Vieques record was not used subsequent to AD 1700 (see Supplementary Information).

Formation of regional sediment composite series. In the process of forming regional composites, we attempted to eliminate redundant representation of unique events among multiple contributing records. Multiple events among contributing sites within a region that fell within the 1σ age model uncertainties of each other were consolidated to represent a single assumed landfall event. This decision was motivated by the fact that known landfall events falling within the modern historical observational period are often recorded at more than one site within an identified region. The date and 1σ ranges for the consolidated events were defined as the average of the dates and ranges of the contributing events. When multiple events from one site fell within the age model uncertainties of an event from another site, the consolidation was done for the event for the first site that was closest in nominal age to that of the second site.

Formation of a basin-wide sediment composite series. To estimate basin-wide hurricane activity from the available regional composites, we normalized each regional event composite by the number of events in that composite, and then weighted the normalized sequence of events by the estimated modern return period for that region (see 'Estimation of return periods' section below). This process ensures that each site contributes to the estimated basin average in proportion to the modern frequency of landfalling hurricanes for that region, simulating the process by which any underlying basin-wide activity is expressed in terms of regional landfall activity. The results of the analysis were not especially sensitive, however, to whether or not the data were normalized, as shown in Supplementary Fig. 1. The basin-wide composite was considered as terminating in the year of the last recorded event. The latest such year in any of the chronologies was 1991.

Monte Carlo ensembles. A nominal chronology of basin-wide landfalling hurricane occurrences is defined by the weighted composite as described in the 'Formation of a basin-wide sediment composite series' section above. However, this nominal chronology does not take into account age model uncertainties in the chronologies. To take into account the impact of age model uncertainties, we performed Monte Carlo experiments using ensembles of 2000 realizations in which the individual events in the regional chronologies were randomly perturbed within their estimated $\pm 1\sigma$ radiocarbon age model uncertainties. We then defined a probabilistic time series of basin-wide landfalling hurricane rates as the maximum values over this ensemble, that is, the time sequence of the maximum occurrence rates for each year that are consistent with the event chronologies and their uncertainties.

Estimation of return periods. We estimated landfall return periods for weighting our sites on the basis of estimated return frequencies for storms striking within a 270-km radius of the site, obtained by the HURISK statistical modelling described in ref. 19. The radius of 270 km was chosen in order to have a large enough area for obtaining appropriate statistics using the HURISK model, yet small enough that the return periods reflect the relative activity at a site compared to the others within the composite. The radius of hurricane impact for each site is probably less than 270 km, and therefore the return periods for overwash at each site would probably be longer than those predicted using this radius. However, these derived return periods are used only to obtain relative weights when assimilating the different records, with actual return frequencies determined by the reconstructions themselves.

It is likely that the various sites differ in the category of storm they are sensitive to. For example, the Alder Island and Mattapoisett sites are probably recording storms of category 2 or greater[8,15]. Although there are no modern deposits at Western Lake, Florida, making it difficult to assess the exact sensitivity of the site, ref. 7 estimates a likely sensitivity to a storm of category 4 or greater. The remaining sites are probably sensitive to storms of category 3 or greater.

The return periods for storms at each respective site based on the HURISK model given the above-assumed sensitivities are as follows (parentheses indicate the 5% and 95% uncertainties in years). (1) Mattapoisett, Massachusetts (≥category 2): 8.52 years (6.31, 13.09); (2) Alder Island, New York (≥category 2): 10.15 years (7.35, 16.43); (3) Singleton Swash, South Carolina (≥category 3): 7.84 years (5.90, 11.69); (4) Western Lake, Florida (≥category 4): 45.66 years (27.69, 129.98); (5) Vieques, Puerto Rico(≥category 3): 5.37 years (4.22, 7.39).

All distinct events were included in regional composites, so the chronologies of the regional composites are dominated by the individual sites with the largest number of contributing events and shortest return periods. Return periods for the regional composites were therefore defined by the most active site contributing to the composite. The mid-Atlantic composite was accordingly assigned the Alder Island return period, while the New England composite was assigned the Mattapoissett return period.

For comparison, we also examined the case where the HURISK return periods used for weighting were instead assigned based on an assumption of uniform sensitivity to a major hurricane (that is, a storm of category 3 or greater) passing within 270 km of each site. (1) Mattapoisett, Massachusetts: 23.81 years (15.5, 51.3); (2) Alder Island, New York: 25.71 years (16.25, 61.45); (3) Singleton Swash, South Carolina: 7.84 years (5.90, 11.69); (4) Western Lake, Florida: 8.78 years (6.58, 13.16); (5) Vieques, Puerto Rico: 5.37 years (4.22, 7.39).

Alternative results from those shown in the main article based on using these latter landfall return period estimates are provided in Supplementary Information. For completeness, we also considered the extreme (and rather implausible) case where all sites are assumed to have equal return periods (Supplementary Information). In all cases, the basic features of the basin-averaged record are preserved (for example, the elevated activity during the interval AD 900–1100), but the detailed evolution differs.

Finally, an assessment was made of the robustness of the basin-wide composite with respect to the contributions of each of the five distinct regions using a traditional jackknife analysis wherein each of the five regions were eliminated one-by-one, and composites were performed using only the four remaining regions. The resulting five jackknife surrogates are shown in the Supplementary Information. The spread among the five jackknife surrogates defines the standard errors shown in Fig. 3 for the sediment composite record.

Modern calibration and validation of statistical model. The statistical model was trained over the full (1870–2006) 137-year interval of overlap between the available instrumental climate state variables and historical tropical cyclone count record as in ref. 3, and the same split calibration/validation procedure, wherein the model was alternatively calibrated and validated over the half-intervals 1870–1938 and 1939–2006, was used. The same instrumental data products were used as in ref. 3, including blended HadCRU/ERSST/Kaplan[31–33] instrumental SST products for the Aug–Oct MDR SST and Dec–Feb Niño indices, and the CRU (ref. 34) Dec–Mar NAO series. We note that the Niño3 index of ENSO (rather than the Niño3.4 index favoured in ref. 3) was used, because a palaeoclimate reconstruction is available only for the Niño3 index and not for the Niño3.4 index. As noted in ref. 3, however, which Niño index is used has very little influence on the resulting statistical model (statistical model resolved variance is 45%/41% for full calibration/validation, as compared with 50%/43% in ref. 3). For sake of comparison, the instrument record-based statistical model was extended back in time from 1870 to AD 1851 using the longer-term instrumental data provided by refs 17 and 18, as shown in Fig. 2.

As discussed in the main text, the historical tropical cyclone record was corrected for an estimated average undercount of 1.2 storms before aircraft reconnaissance began (pre-1944) as in ref. 3, but the conclusions of our study are insensitive to whether this estimate, or the more sizeable undercount bias argued by Landsea *et al.* (see refs 2, 29) is used (Supplementary Information). Additional tests performed elsewhere[35] have used an alternative series we term the 'MDR residual' (MDR SST minus the global tropical mean SST during Aug–Oct), which has been argued in certain studies[36,37] to be a better predictor of tropical Atlantic tropical cyclone counts than the MDR SST itself. These tests reveal the MDR residual to be an inferior predictor to MDR SST across all reconstruction skill metrics; in particular, the statistical model cannot reproduce the positive trend of the past two decades when the MDR residual is used as a predictor instead of MDR SST.

The statistical model was examined for adequacy with respect to regression assumptions (that is, that the assumption of Poisson-distributed regression residuals is met), based on χ^2 and likelihood-ratio tests. The statistical model trained over the full 137-year period has a residual deviance of $D = 107.98$ with $N = 133$ degrees of freedom. A χ^2 test indicates $\alpha = 0.945$ (that is, a 95% chance that we would be incorrect in rejecting the null hypothesis of Poisson-distributed residuals). The null deviance (that is, the residual deviance for an assumed fixed-rate Poisson process) is $D = 196.91$ with $N = 136$ degrees of freedom. A likelihood test based on the difference $\Delta D = 88.93$ with $N = 3$ degrees of freedom indicates a statistical significance of $P = 0.0$ for the statistical model itself (that is, a 0% chance that we would be incorrect in rejecting the hypothesis that the model coefficients for the three predictors are all zero).

Statistical prediction of tropical cyclone counts using proxy reconstructions. Here the model was applied to decadally resolved reconstructions of MDR SST and Niño3 described by ref. 17 and the decadally smoothed winter NAO index of ref. 18. For the instrumental interval (1851 to present), standard errors due to uncertainties in the model coefficients were calculated from the residual decadal variance diagnosed from the validation residuals (standard errors were averaged for the early and late intervals of the split calibration/validation procedure). For the pre-1851 statistical model estimates, which are driven by reconstructed climate indices, there is an additional component of uncertainty due to the uncertainties in the climate indices themselves. This contribution was estimated by Monte Carlo simulations in which the statistical model was driven with an ensemble of 2000 randomly perturbed versions of the statistical predictors consistent with their estimated uncertainties[17], and an additional random term due to the uncertainties in the model coefficients.

Finally, to determine the separate roles of the individual predictors, we performed statistical model runs in which each of the predictors (NAO, MDR SST and Niño3) was kept constant at its modern climatological mean value, while the other two predictors were allowed to vary (Supplementary Information).

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